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Virtual Building for Construction Projects

Laurel M. Sheppard

Although computer-aided design is widely used in the architecture-engineering-construction (AEC) industry, the exchange of information is still largely a manual process, where 2D paper drawings are reviewed to identify conflicts. Obviously, this process is time consuming and inefficient —not only do many conflicts go undetected but it's nearly impossible to quickly determine how design changes will affect the project's cost and schedule. Thus, an average project will lose 8 to 15 percent of labor costs due to mistakes that cause change orders, delays, and rework.

Project management tools also have limitations. Since they use critical path method schedules, such tools don't show the three dimensions of space and the fourth dimension of time, making it difficult to visualize and communicate the schedule and analyze the sequence of construction. Cost estimating is another mostly manual process that increases a project's time and decreases its accuracy. Software that links design components with a cost database and scheduler could overcome these problems.

Enter 4DCAD technology, which in its simplest form links 3D models to schedules. More advanced versions link costs and other data. Instead of just reviewing printed flow diagrams, users can visualize the construction sequence as a movie or animation. This avoids conflicts in scheduling and resolves safety issues (such as erecting steel over where people work) before actual construction begins.

The outcome is increased productivity and decreased waste on job sites. Research at Stanford University estimated that 4DCAD helps avoid up to 45 percent of change costs, leading to a minimum of 4 to 6 percent overall project cost savings. Since construction projects can cost billions of dollars, these savings become quite significant. Another major benefit of 4DCAD is improved communication between all participants involved with the designing and scheduling of a construction project.

Challenges and limitations

Despite these benefits, one of the largest barriers to implementation (at least in the conventional AEC industry) is that 4DCAD technology requires engineering designs as 3D models, something currently uncommon. From 75 to 80 percent of a 4D model's cost involves creation of the underlying 3D model. When the design team works in 3D, that cost becomes a project benefit. Model costs on large projects might run as low as one-half a percent of the project budget, yet be returned 50 to 100 times over in project savings. However, if project participants don't clearly establish a 4D model's scope and purpose and level of detail prior to its modeling, the cost-benefit ratio decreases.

In the cases of processing, power, and offshore plants—which are much larger projects than the typical AEC project—most projects' conceptual and detailed design and engineering phases produce a 3D model. For these projects, the owner-operator generally becomes the biggest obstacle to 4DCAD technology because of the desire to minimize costs in each project phase. The owner subcontracts each phase to the lowest bidding firm, and thus data created during each phase is rarely passed electronically to the next phase.

Another problem is that 3D models need to accommodate the 4D modeling process. 4D modeling requires significant project scope and schedule information, which might not be available. The better the schedule the easier it is to build a 4D model. The 3D models might be inconsistent in geometry or schedule data, lack data in some areas, be too data heavy in others, or lack enough detail. The geometry definition might conflict with the schedule, making it difficult to link the two. However, providing a software tool to map construction organization of the facility to design organization can avoid these problems.

Current commercial systems

Although 4D modeling efforts might have begun as early as 1973, it was not until 1984 that visual construction simulation software became commercially available with the introduction of Construction Systems Associates' PM-Vision. In 1986 Bechtel developed a 3D animated design review tool called Walkthru for Silicon Graphics workstations, which they later ported to the PC. Jacobus Technology, established in 1991 by former Bechtel employees, developed an interface between Walkthru and a CAD system; later they integrated Walkthru with Primaver's P3 scheduling program. Jacobus marketed this system as the Construction Simulation Toolkit, and further work led to the development of a real-time 3D visualization system called Navigator. (Bentley Systems acquired Jacobus in 1997.)

During the development of Navigator, Stanford University's Center for Integrated Facility Engineering applied the toolkit to build a 4D model for the San Mateo County Health Center, the first application involving a

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nonindustrial facility. Around this time, Bentley Systems' Schedule Simulator and Intergraph's Schedule Review came on the market. These programs had two major limitations: a new 4D model was necessary for every new situation or for different levels of detail, and it was not possible to make changes to the 4D model and simultaneously update the 3D model and the schedule.

Bentley and Intergraph have continued to improve their products to address these issues. Bentley merged their Schedule Simulator with Navigator, which visually simulates the construction process by integrating detailed 3D models with critical scheduling and planning information. The software easily generates simulations of construction schedules, heavy lifts, material handling, equipment placement, and operations/maintenance activities, providing a clear understanding of object motions and potential clashes in the area of activity.

Sinclair Knight Merz (SKM), a global consulting firm in Australia, implemented Navigator during its capacity expansion project for an iron ore processing and export facility in Port Hedland, western Australia. The company chose Bentley Navigator because of its functionality; ease of use, implementation, and setup; low administration overheads; and open object architecture, according to Trevor Black, group CAD manager for SKM. Navigator provided a means to take data from multiple sources, view and report from a consolidated model, and increase interoperability between project partners.

Navigator reduced variations caused by misinterpretation of scope and documentation. SKM also walked maintenance crews through the project's car dumper (a mechanical device that unloads freight cars) prior to the letting of contracts. Their input regarding maintenance access and other related issues resulted in some design changes. This led to large savings in rework or post-project modifications to the plant. The company carried out a hazardous operations review of the car dumper using the model in Figure 1. This resulted in a 50 percent savings in time, when converted to cost savings that actually covered the cost of the software.

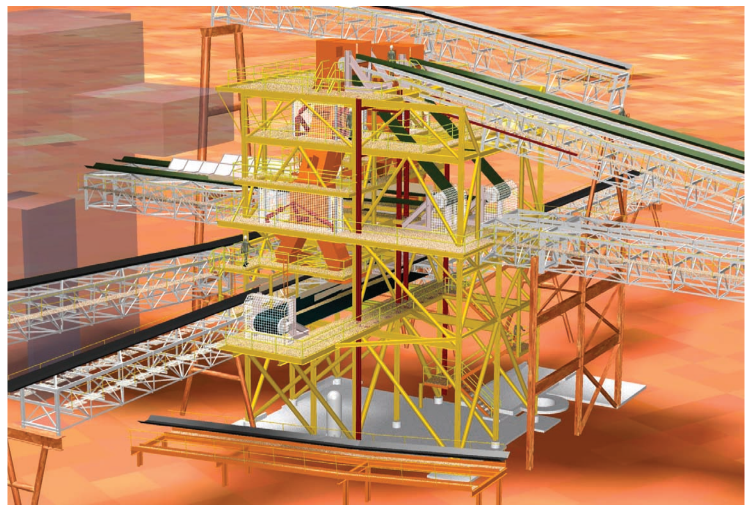
SKM made the models available onsite to construction contractors. They constructed many of the transfer towers around existing conveyors whose operational downtime had to be kept to a minimum. This required complex construction sequences that SKM explored using the simulation software (see Figure 2).

Intergraph Process, Power & Offshore has explored construction visualization for the last 5 years of its 20-year history in creating 3D visualization software. Its SmartPlant Review is a Windows-based visualization software that can handle 3D models ranging from 3 to over 300 Mbytes. The tool is integrated with Intergraph's Plant Design System. SmartPlant Review's modular format lets companies add features only when needed. These include modules for construction, simulation and visual effects, collaboration, and onsite drawing generation. The collision detection function displays objects that might collide in a defined movement path, such as during equipment installation or removal of equipment for maintenance (see Figure 3).

Westinghouse Electric used SmartPlant Review and Plant Design System to visualize the construction sched-


Courtesy of SKM

1 The car dumper was a challenging engineering exercise as the dumper was around 40 meters deep and the ground water table was around 2 meters.


Courtesy of SKM

2 Sinclair Knight Merz used the transfer station model for a construction simulation to highlight construction's complex nature. They built the transfer towers around existing conveyors (shown).

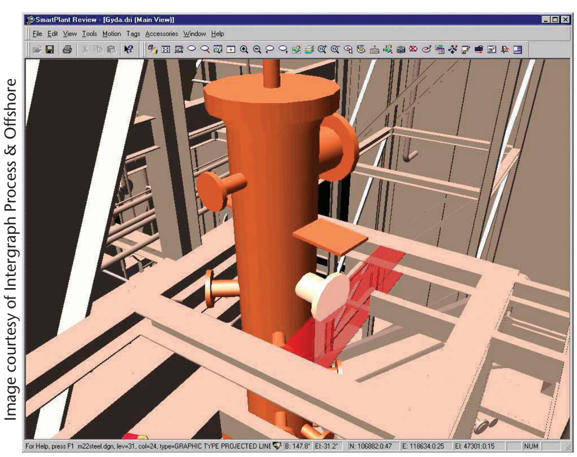


Image courtesy of Intergraph Process & Offshore

3 As a horizontal vessel is lowered and rotated into place during a construction sequencing review, a flange collides with a beam. SmartPlant Review has highlighted the steel beam in transparent red.

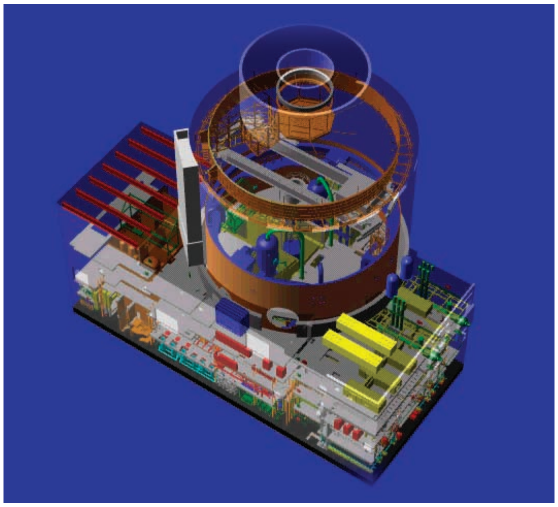


Image courtesy of Intergraph Process & Offshore

4 Overview view of the AP600 model developed with SmartPlant Review.

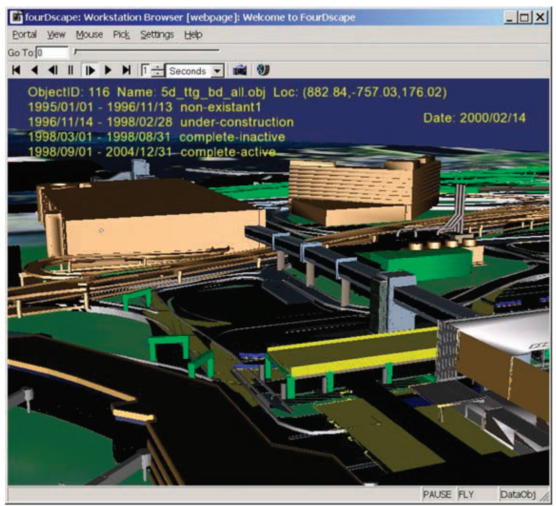


Image courtesy of Balfour Technologies/Massport

5 Construction phasing at Boston's Logan Airport using fourDscape. Color coding shows construction phases, enabling managers to foresee schedule conflicts.

ule and activities of its AP600—a 600-MW advanced pressurized light-water reactor plant—and eliminated three to five months from the schedule through logic and design changes alone. Westinghouse determined that each day of construction removed from the schedule was worth at least 70,000 dollars to the owner in cost avoidance. Just one change found using this tool allowed Westinghouse to take six weeks off the critical path, reducing costs by more than 2 million dollars. Figure 4 shows an overview view of the model.

This change involved realigning the schedule to put rebar for the containment internal structure into the lower containment vessel head before its placement on the site foundation. Initially this placement was scheduled to occur onsite, in the hole, after placement of the containment vessel, which caused six weeks of rebar work on the critical path. Westinghouse only discovered this when viewing the 4D construction, not in the standard review of the schedule. Redesigning some component foundations also allowed for quicker construction.

The size and complexity of the 3D model required Westinghouse to fine-tune its use of SmartPlant Review. "First, the model was broken into separate buildings," explains Jill Clelland, information management lead of Passive Plant Projects & Development. "Second, for view manipulation, the view cone was shortened. This is the feature that tracks all of the elements that will be redrawn." In other words, a view cone determines what the application's eyes can see, such as limiting the view to only the first 50 feet from the eye point, and only a 40-degree field of view. By limiting this cone view, fewer items are processed.

More recently, other companies have entered the 4DCAD market, including Balfour Technologies, Common Point, and Reality Capture Technologies. All continue to improve their softwares' capabilities, which vary in cost and functionality. As these improvements continue and costs reduce, usage should increase.

Balfour Technologies

Balfour Technologies' fourDviz technology grew out of a joint collaboration between Balfour Computer Systems and Infinity Technologies (Balfour Technologies' predecessor companies). The software was originally an in-house tool for producing 4D visual deliverables for transportation consulting contracts. It's based on flight simulation technology and company cofounder Robert Balfour's doctoral research in temporal visualization and computer-generated holography fueled further development of this tool.

After its launch in 2001, the company licensed fourDviz software to several clients. Boston's Logan Airport Modernization Program first used fourDviz (now available as fourDscape) onsite as a construction planning and management tool (see Figure 5). Simulations created in conjunction with Auburn University for a project planned for Huntsville International Airport in Alabama later employed the software.

Balfour and Infinity merged in 1999 to form Balfour Technologies. In 2003 Balfour announced fourDscape, which incorporates a desktop browser that lets users visually integrate and analyze multidimensional data flows in a collaborative environment. FourDscape users interact with 3D visual models driven by datasets of time-dependent information, with complete control of stepping forward or backward in time to identify cause and effect relationships between the visualized datasets.

Using fourDscape the user opens a hyperlink to a URL for a 4D portal server, gaining access to 3D models and datasets integrated into a 4D landscape. Using the mouse, the user interacts with the 4D scene, using VCR-like buttons (pause, play, stop, fast forward, rewind) on the toolbar to move in the four dimensions of time and space. A unique collaborative feature in fourDscape is the ability to handoff a local fourDscape GUI to a remote user connected to the same 4D portal.

Previous fourDscape application areas include transportation planning, engineering and intermodal facilities logistics, and design and construction management. Demonstration projects have included warehouse operations analysis and real estate management. A new project is scheduled for a New York Department of Public Works and Health study. However, Balfour's technology is generally application independent (just like a Web browser) and can visualize almost any time-dependent data that needs analysis.

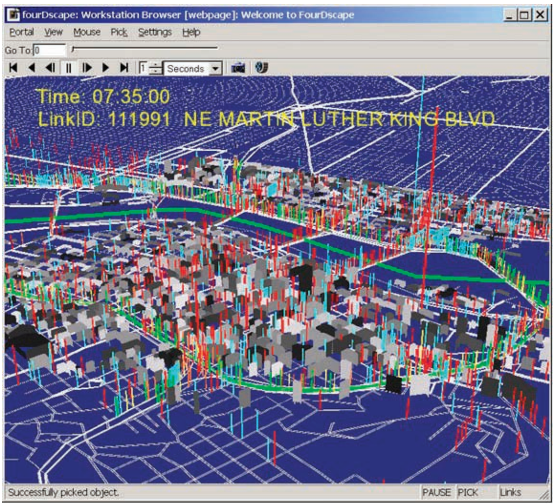


Image courtesy of Balfour Technologies and IBM Business Consulting

6 **Transportation forecasting in downtown Portland, Oregon using Transims and fourDscape. Visualizing simulated traffic patterns enables effective planning, yielding improved transportation infrastructures for predicted traffic volumes.**

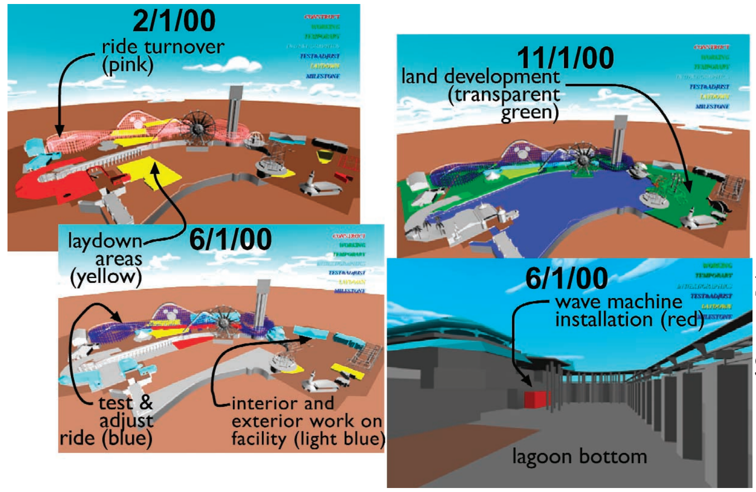


Image courtesy of Common Point

7 **4D snapshots of Common Point 4D, supporting sequence and development of project milestones for Paradise Pier in Disney's California Adventure by Walt Disney Imagineering.**

IBM's Transims, a transportation modeling and forecasting software package, uses fourDscape for visualizing results of simulations including vehicular traffic, emissions, and transportation infrastructure performance data. fourDscape was selected because it met the company's requirements regarding performance and cost. "We needed a 4D visualization package capable of handling the tremendous size of datasets generated by Transims," explains Jason Dulnev, IBM Business Consulting Services' principal consultant and the Transims project's technical manager. "For example, a single traffic dataset for a medium-size city can easily exceed 1 Gbyte in size."

To integrate fourDscape with Transims, IBM adapted the product to access Transims-specific file formats, and some additional functionality was added. The fourDscape GUI was also streamlined to optimize the number of steps needed to activate various capabilities. To date there have been two implementations of Transims models—in Blacksburg, Virginia and Portland, Oregon. Figure 6 illustrates transportation forecasting for the latter.

Common Point

Common Point's Common Point 4D is a tool based on a middleware platform that targets the entire design, construction, facility operations, and capital asset management market. It originated from joint research between Walt Disney Imagineering and Stanford University's Center for Integrated Facility Engineering. The tool lets design and construction professionals review and reorganize the 3D model and corresponding construction schedule at several levels of detail and in several integrated computing environments, such as desktop, Web, and VR (using a CAVE).

A hierarchical approach allows links between any level of detail of the 3D model and construction schedule. Users can easily group product components into construction zones, enabling customization of the content, view, and level of detail for any visualization. Users can also efficiently update a 4D model because they can make changes at any level. The latest version has an enhanced set of CAD adapters and integration tools. It provides Graphisoft's ArchiCAD, AutoDesk's Architectural Desktop (ADT), and Bentley's Microstation with the ability to give full attribute and type extraction from ADT objects and the ability to dynamically and remotely link to CAD files, automating the update and import process at a file or folder level.

The first application of Common Point's 4D software was the strategic planning of the construction sequence for Paradise Pier within Disney's California Adventure. Walt Disney Imagineering used the software to develop and review track erection sequence options. This sequence had to assure that the ride test and adjust procedures were completed to support opening day, three years from this planning stage. The final construction sequence needed to maximize productivity for construction and erection of the lagoon and the six attractions placed under, within, and directly adjacent to the coaster track.

The launch portion of the track lies just above the lagoon's surface. Therefore, Walt Disney Imagineering had to fill the lagoon prior to the test and adjust procedures. In addition to the launch and other portions of the coaster track, the footprints of three independent attractions lay within the lagoon. To effectively communicate the erection options including material lay-down areas and crane pads, the 4D model also provided erection sequences for two other attractions (see Figure 7).

Walt Disney Imagineering successfully used the 4D tool to determine the optimum contractual sequence of the work, which was divided into two stages. The first stage included all deep foundations for the coaster, a rough-graded lagoon, and foundations within the lagoon. This stage was bid and constructed concurrently with the completion of design documentation for the

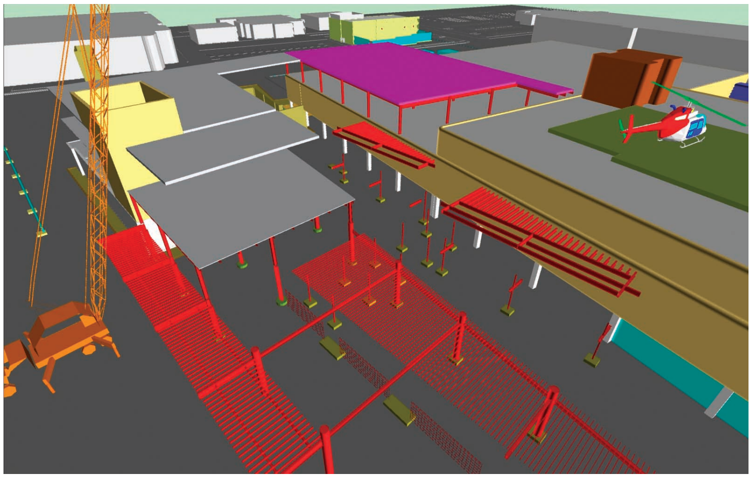


Image courtesy of Common Point

8 DPR Construction used 4D models to coordinate hospital operations with construction; this 4D model snapshot shows the steel erection next to the medivac helicopter flight path.

balance of the work. The second stage was bid at more or less substantial completion of the first stage and bid results were within +/–2.5 percent of the budget.

Using VR reduced the time needed to resolve construction problems from several hours to less than 10 minutes. The scheduler also considered 20 different design and schedule scenarios over a two-week period. Communication became more effective as well: the owner's project management team made clear the restricted lay-down space and access routes to the general contractors, who in turn used the 4D model to show their subcontractors the project's challenges.

In another application of Common Point 4D, DPR Construction used 4D models to help an owner visualize the future and demonstrate to hospital administrators at Banner Health Good Samaritan Hospital in Phoenix, Arizona that DPR had the best approach for maintaining 24/7 operation of critical care facilities. Administrators subsequently used the 4D models to educate physicians and staff about what would happen during each construction stage. The improved communication between hospital and construction staff helped minimize the risks to the hospital operations. For example, the 4D model alerted the hospital to the need to change the medivac helicopter's flight plan during steel erection in a timely manner so that the necessary FAA approvals could be obtained (see Figure 8).

Applications of Common Point 4D since 1998 have included more than 70 projects ranging from large-project and campus strategic planning, construction and facility operations coordination, overall design and construction coordination, site logistics and construction methods improvement, and scope-of-work planning. Additionally, students at more than 15 universities use the software to support research and development and design and construction management courses.

Construction Systems Associates

In 1984 CSA developed PM-Vision, an application that used 3D CAD to depict the sequence of a construction project. The company marketed the software until 1989, when CSA realized that practical application of this technology would be too expensive. Around 1995, CSA expanded the PM-Vision module considerably, adding new functions and a new user interface. "Acceptance of this technology is considerably higher than it was 20 years ago," says Amadeus Burger, CSA president.

PM-Vision integrates a 3D CAD plant model with a project schedule, allowing visual representation of this schedule, as well as use of the database to support the presentation of a cost-effective schedule and analysis of sequence and resources for implementation. The software is based on CSA's master model technology, which is a large-scale facility database integrated from a variety of sources and formats, including schematics, text, and documents. The model reorganizes the plant by construction zones and type of systems, for example electrical or plumbing. The user can also apply different organizational structures (engineering versus construction) to the model.

Objects in the model are parametric objects. Each object is a mathematical representation of an object type that resides in the master database that contains the object's physical data and a data parameter series relating to the object's characteristics. As an object is placed in the model, the software draws data from the master database and any imported data linked to the object. Users can query every object in the model for available data and linked documents and reference information.

PM-Vision transfers schedule activities from the scheduler along with activity attributes to the software's database. Attributes include location codes, disciplines, and responsibility codes. Users can extract partial schedules to create a specific review schedule for a certain subcontractor, discipline, or building. The database can also contain multiple versions of schedules to assess impact of various assumptions and changes. The model database has no size and complexity limit. The user can reorganize the data to match the schedule. Once the user determines a schedule they have a wide variety of display options, including schematic diagrams and graphical displays of work content for a specific activity.

Westinghouse Electric Nuclear Systems is one of a number of companies that have used PM-Vision. For this company, the software saved 15 percent in construction time after modeling a nuclear power plant. Intel Corporation also used the software for its D1D fab project located in Hillsboro, Oregon (see Figure 9). The pilot's scope included all of the civil, structural, architectural, process, and mechanical requirements for four buildings, totaling over 1 million square feet.

To save time and effort, rather than redraft the 2D design in 3D, Intel converted its model into three dimensions. Although this conversion was a significant portion of the pilot's cost—around 75 percent—it only took several weeks. An interface module converted the project model into a tree structure, allowing quick and easy access.

Automatic interference checking reports, highlighting conflicts between systems and assemblies, was one of the most useful aspects of the integrated modeling approach. Resolving these conflicts resulted in signifi-

cant cost savings. Out of a total savings of 2.45 million dollars for the entire project, Intel attributed about 50 percent to resolving schedule conflicts. The process also revealed design problems; for instance, Intel changed light fixture locations based on light pattern blocking identified in the model.

Reality Capture Technologies

Similar to CSA's PM-Vision, Reality Capture's ConstructSim is based on a virtual plant model and dynamically integrates 3D CAD, engineering systems, project schedules, project control databases, materials management systems, as-built data, and other digital information. The plant model links applications and databases into a distributed network and allows use of engineering design data for start-up, operations, and maintenance phases of a facility's life cycle. An XML framework provides interfacing with project controls and material management systems.

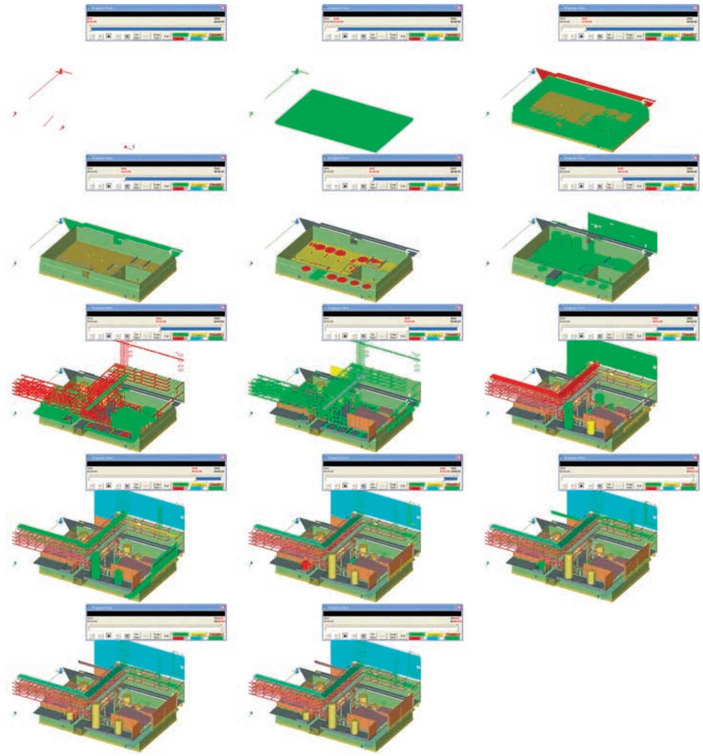
ConstructSim automatically organizes the engineering design model into constructible elements so that the virtual model represents the way the facility is built, not just the way it is designed. Model components are isolated based on process systems, construction zones, or other user-defined attributes, and automatically create logical group detailed tasks. After construction zones are defined, the engineering design model is automatically organized according to craft (pipe, mechanical, civil) and zones. Users can then quickly query and display model components. ConstructSim also incorporates additional intelligence such as process flow models to enable advanced features such as following a pipeline.

As the tasks are detailed, the tool generates a 4D construction schedule simulation by automatically associating each detailed task with the respective schedule activity identification. The software also generates detailed weekly work packages (see Figure 10), followed by a bill of materials that is synchronized with the materials management system. As tasks are completed, ConstructSim synchronizes with the project controls system to update task status in the model and provide the ability to visually monitor detailed project progress within the virtual model (see Figure 11, next page).

One major difference between ConstructSim and other software is its ability to automatically update the virtual plant model. Other systems require manual updating, which can be a resource drain on users. ConstructSim is also user friendly due to its joystick-based operation.

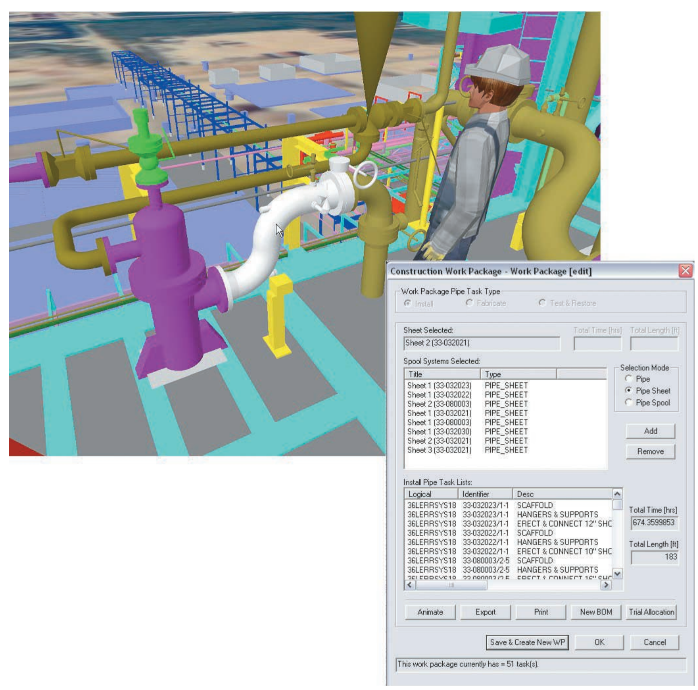
One expansion project that implemented ConstructSim saw the elimination of four to five project personnel and the reduction of total installed construction costs by more than 4 percent. This project required adapters to enable the dynamic integration of a 3D CAD system and project schedule as well as the constructor's proprietary materials management system and project control applications.

This project mainly used ConstructSim as a tool for interactive planning and field execution of weekly work packages for piping. To support the interactive weekly work planning, ConstructSim automatically produced a detailed level-4 task plan (a schedule that details the



9 **Simulation of a construction schedule for a portion of a large-scale semiconductor facility. Yellow indicates activity in progress, red means critical-path activity, green signifies activity completed. After the activity has completed processing, the geometry changes to its original color.**

Image courtesy of CSA



10 **ConstructSim displays work package creation where users plans the ideal grouping of materials into work packages weeks before mobilizing for these activities in the field. Colors within the picture represent different process systems except for the white spool, which means it's selected for addition to the work package.**

Image courtesy of Reality Capture Technologies

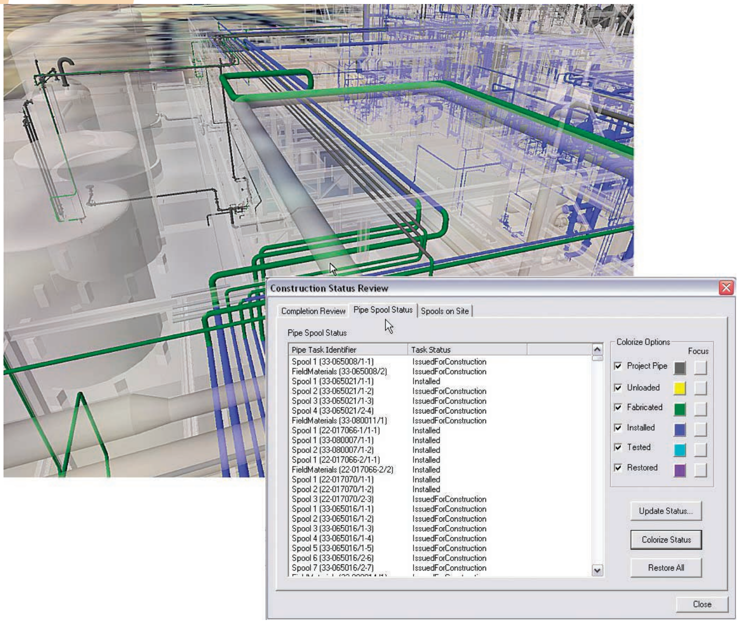


Image courtesy of Reality Capture Technologies

11 **ConstructSim displays construction status review where users visually monitor construction execution status and colorizes the model based on work completed and needing to be completed. Colors represent items, as follows: gray for project piping, yellow for unloaded pipe, green for fabricated pipe, blue for installed pipe, cyan for tested pipe, and purple for restored pipe.**

Links To Learn More

- Balfour Technologies (http://www.BAL4.com/)
- Bentley Systems (http://www.bentley.com/products/navigator)
- Center for Integrated Facility Engineering, Stanford University (http://cife.stanford.edu/)
- Common Point (http://www.commonpointinc.com/)
- Construction Systems Associates (http://www.csaatl.com/gallerymovies.shtml)
- Intergraph (http://ppo.intergraph.com/visualization)
- Reality Capture (http://www.reality-capture.com/)

Related Articles

- B. Fröhlich et al., "Collaborative Production Modeling and Planning," *IEEE Computer Graphics and Applications*, vol. 17, no. 4, 1997, pp. 13-15.
- Technical reports and working papers published by the Center for Integrated Facility Engineering can be obtained from CIFE's Web site; http://cife.stanford.edu/Publications/index.html.

tasks associated with work packages) of over 25,000 steps for piping, based upon a seed level-1 (milestone) master schedule of approximately 100 activity items.

The prioritization of procurement and the ability to monitor the delivery of spools onsite paid off early in the project. As the project team mobilized in the field, pipe spools began to arrive late, and the majority of pipe spools that did arrive were those for the upper levels of the structure that was to be erected, not the lower levels where the pipe team could gain access for installation. The team could easily determine the areas where installation could begin based on the availability of materials.

In addition, the team used priority information for fabrication sequencing to help expedite spool delivery in the construction areas so that the project team could begin pipe installation. ConstructSim workstations in the field supported engineering for the construction crews (reducing requests for information), and those in the project management offices monitored task progress on a daily basis and identified conflicts and issues before they became problems in the field.

Future outlook

As advancements continue, 4DCAD will eventually become the standard for all phases of facility design, engineering, and life-cycle engineering regarding operations, maintenance, and retrofit. It will also expand to e-commerce to improve procurement of materials and services. However, a shared project model will have to be developed, as well as reliable electronic information exchange standards. Faster information exchange will keep data up to date and help identify discrepancies.

A move to more open platforms will also improve the ability to move data intelligently throughout the life cycle and between project partners. In addition, developing shared models requires a change in mindset to view facilities design, construction, and operations in a holistic or integrated manner instead of as separate entities. In turn, all principals involved must work more closely together.

According to Robert Christian, a senior manager of business development for design systems at Intergraph Process, Power & Offshore, "The 4D tool of the imminent future is one that combines data and workflow management and 3D and 2D design, integrated multidiscipline engineering tools in a single environment that does not rely on now-outmoded CAD packages." ■

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Readers may contact Laurel Sheppard at lashpubs@infinet.net.

Contact editor Mike Potel at potel@wildcrest.com.